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TITLE A THEORETICAL PREDICTION OF CRITICAL HEAT FLUX IN SUBCOOLED POOL BOILING DURING POWER TRANSIENTS

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NOMENCLATURE

A_v	Heater area cover by vapor (m^2)
A_w	Total heater area (m^2)
B_e	Switch-over parameter (dimensionless)
$C_{p,\ell}$	Specific heat of the liquid (J/kg)
d	Heater diameter (m)
$f_1(P)$	Prescribed function of pressure, defined after Eq. 2
$f_2'(P, \Delta T_{sub})$	Prescribed function of pressure and subcooling, defined after Eq. (9)
$f_3(P, \Delta T_{sub})$	Prescribed function of pressure and subcooling, given by Eq (6)
g	Gravitational acceleration (m/s^2)
$H(\ )$	Heavy-side step function
h_{fg}	Latent heat of vaporization (J/kg)
Ja	Jacob number (dimensionless)
Ja^*	Modified Jacob number (dimensionless)
K	Empirical correction factor (dimensionless)
K^*	Modified empirical constant (dimensionless) defined after Eq (8)
q	Surface heat flux (W/m^2)
$q_{CHF,SS}$	Steady-state CHF (W/m^2)
$q_{CHF,TR}$	Transient CHF (W/m^2)
t	Time (s)
V_1	Vapor mass volume growth rate (m^3/s)
δ	Liquid-layer thickness (m)
δ_c	Critical liquid-layer thickness (m)
$\delta_{c,o}$	Critical liquid-layer thickness at steady-state CHF level (m)
ΔT_{sub}	Degree of subcooling (K)
η	Ratio of transient CHF to steady-state CHF (dimensionless)
σ	Surface tension (N/m)
ρ	Density (kg/m^3)
ξ	Volumetric ratio of accompanying liquid to moving bubble (dimensionless)
λ_D'	Modified Taylor unstable wavelength (m)
τ	Exponential period (s)
τ_d	Vapor mass hovering period in saturated pool boiling at steady-state CHF (s)
τ_g	Vapor mass growth period in subcooled pool boiling at steady-state CHF (s)

<u>Subscripts:</u>

B	Switch-over point
f	Saturated liquid
g	Saturated vapor
i	Initial value
ℓ	Subcooled liquid
max	Maximum
min	Minimum
sat	Saturated pool boiling
sub	Subcooled pool boiling

A THEORETICAL PREDICTION OF CRITICAL HEAT FLUX IN SUBCOOLED POOL BOILING DURING POWER TRANSIENTS*

by

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ABSTRACT

Understanding and predicting critical heat flux (CHF) behavior during steady-state and transient conditions are of fundamental interest in the design, operation, and safety of boiling and two-phase flow devices. This paper discusses the results of a comprehensive theoretical study made specifically to model transient CHF behavior in subcooled pool boiling. This study is based upon a simplified steady-state CHF model in terms of the vapor mass growth period. The results obtained from this theory indicate favorable agreement with the experimental data from cylindrical heaters with small radii. The statistical nature of the vapor mass behavior in transient boiling also is considered and upper and lower limits for the current theory are established. Various factors that affect the discrepancy between the data and the theory are discussed.

I. INTRODUCTION

Boiling heat transfer with time-dependent heat input, as well as the prediction of critical heat flux (CHF) under such conditions, is of interest in several applications. One application in light-water nuclear reactor technology involves the reactivity-initiated accident (RIA), in which

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a sudden increase in power generation rate may occur. A comprehensive understanding and an accurate modeling of CHF are required to evaluate RIA scenarios. In our earlier study,[1] a theoretical prediction of CHF during power transients in saturated pool boiling was presented. There are many practical problems, however, where CHF is reached in the presence of a subcooled liquid. For instance, if a power burst occurs in a pressurized water reactor, CHF conditions may be reached while the bulk of the liquid is highly subcooled. Thus, because of its practical importance, the effect of subcooling on CHF during power transients has been the subject of earlier studies.

The studies of Sakurai *et al.*,[2] Kawamura *et al.*,[3] and Kuroda (as cited by Serizawa[4]) are examples of fundamental research efforts aimed towards the understanding of the subcooling effect on pool boiling CHF during power transients. All of the previously mentioned experimental studies are concerned with subcooled pool boiling in water. Sakurai *et al.*[2] and Kawamura *et al.*[3] experimentally investigated the transient boiling of water at atmospheric pressure with different degrees of subcooling. In these experiments, small flat ribbon heaters were used. In his experiment, Kuroda (as cited by Serizawa[4]) used a horizontal wire heater with a small radius to investigate transient subcooled pool boiling of water. The only data reported in the open literature were based on a 0.993-MPa pressure.[4]

In steady-state subcooled pool boiling, the most commonly used CHF formulation was developed by Ivey and Morris (as cited by Collier[5]). This correlation is given by

$$\frac{q_{\mathrm{CHF,SS,sub}}}{q_{\mathrm{CHF,SS,sat}}} = 1 + 0.102 Ja^* \quad , \tag{1}$$

where the modified Jacob number, Ja^*, is defined as

$$Ja^* = \left(\frac{\rho_\ell}{\rho_g}\right)^{3/4} Ja \quad ,$$

with the Jacob number, Ja, defined as

$$Ja = \frac{C_{p,\ell}\Delta T_{\mathrm{sub}}}{h_{fg}} \quad .$$

Equation 1 shows that, for a given pressure, the ratio of subcooled CHF to saturated CHF is a linear function of the subcooling if the variations of the liquid density and liquid specific heat with respect to subcooling are neglected.

During transient conditions, the same quantitative relationship between subcooling and the ratio of subcooled CHF to saturated CHF may be invalid. The experimental observations[2–4] show that, for a given pressure and rate-of-change of the surface heat flux, the ratio of transient CHF to steady-state CHF decreases as the degree of subcooling increases, which implies

$$\frac{q_{\mathrm{CHF,TR,sub}}}{q_{\mathrm{CHF,SS,sub}}} < \frac{q_{\mathrm{CHF,TR,sat}}}{q_{\mathrm{CHF,SS,sat}}} \quad .$$

Thus,

$$\frac{q_{\mathrm{CHF,TR,sub}}}{q_{\mathrm{CHF,TR,sat}}} < \frac{q_{\mathrm{CHF,SS,sub}}}{q_{\mathrm{CHF,SS,sat}}} \quad .$$

This result also is expected when our theoretical transient CHF model[1] for saturated pool boiling is used. This model shows that the ratio of transient CHF to steady-state CHF is an increasing function of the vapor mass growth period, for a given rate-of-change in the surface heat flux. Fand and Keswani[6] observed that the initiation, growth, and collapse of a bubble during subcooled boiling occur more quickly than the initiation, growth, and departure of the bubble during saturated boiling at the same pressure. In fully developed nucleate boiling in the vicinity of CHF, vapor mass initiation is almost instantaneous. Therefore, it may be concluded from the vapor mass growth period that the ratio of transient CHF to steady-state CHF is a decreasing function of the liquid subcooling.

In the remainder of this paper, these observations are quantified and formulated into a transient CHF correlation. This task requires an appropriate steady-state CHF model for subcooled pool boiling in terms of the vapor mass growth period. In Sec. II, a simple steady-state CHF model is developed. Based upon this model, a transient CHF correlation is presented in Sec. III. In Sec. IV, the developed theory is compared with the experimental data available in the open literature. The statistical nature of the vapor mass and its effect on the transient CHF are considered in Sec. V. Finally, Sec. VI summarizes and concludes the current study.

II. STEADY-STATE CHF MODEL FOR SUBCOOLED POOL BOILING

In this section, a subcooled pool boiling CHF model similar to the saturated pool boiling model of Haramura and Katto[7] is developed. Figure 1 shows the boiling configuration postulated by Haramura and Katto[7] for saturated pool boiling. We assumed that a similar configuration may be valid for subcooled pool boiling with moderate subcoolings. We empirically forced our mathematical model to yield the same result as the correlation given by Eq. (1). Therefore, the current model does not improve the predictive capability for the steady-state CHF. Its sole advantage is that it explicitly includes the vapor mass growth period. In subcooled pool boiling, we use the term growth period as an equivalent to the hovering period in saturated pool boiling. Physically, the growth period may terminate by vapor mass collapse, whereas the hovering period always terminates by vapor mass departure. Our approximate model is based upon the following postulates.

a. The density and specific heat of the subcooled liquid are weak functions of temperature, and they can be approximated by their value at the saturation temperature for the given pressure. This assumption is commonly used in thermodynamics, and it is considered sufficiently accurate for moderate subcoolings.

b. The assumption is made that the fraction of the heater area covered by vapor, A_v/A_w, is unaffected by subcooling. This quantity is formulated by Haramura and Katto[7] as a function of the density ratio only. Because of postulate (a), this ratio remains independent of subcooling. Furthermore, this ratio is not affected by the surface heat flux and is usually very small even at pressures close to the critical pressure.[7]

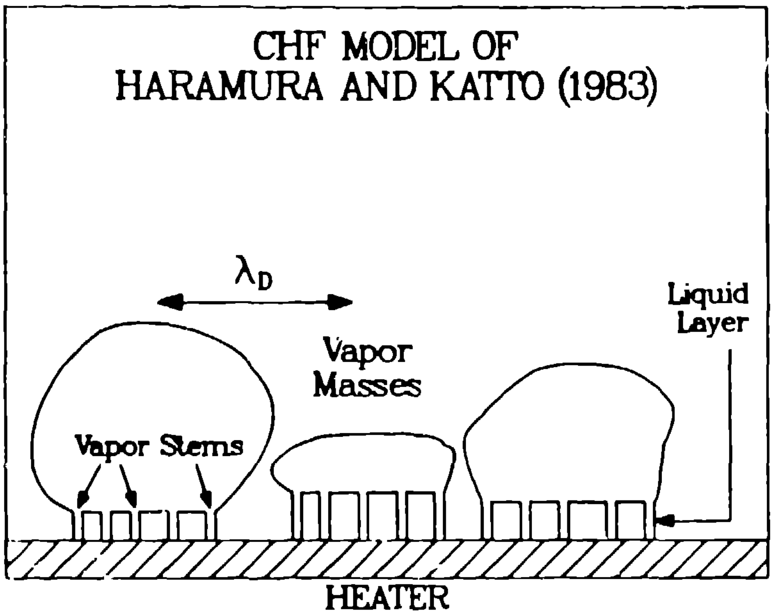

Fig. 1.
Boiling configuration at high heat fluxes near CHF.

c. The critical liquid-layer thickness underneath the vapor mass, as shown in Fig. 1, is a fraction of the Helmholtz instability wavelength in the vapor stems. This wavelength is inversely proportional to the square of the surface heat flux, as formulated by Haramura and Katto.[7] Thus,

$$\delta_c = \frac{f_1(P)}{q^2} \quad , \tag{2}$$

where

$$f_1(P) = \frac{\pi}{2}\,\sigma\left(\frac{\rho_f+\rho_g}{\rho_f\rho_g}\right)\left(\frac{A_v}{A_w}\right)^2(\rho_g h_{fg})^2 \quad .$$

d. As shown in Fig. 1, at high heat fluxes near CHF, the surface is crowded by many vapor masses growing and departing or collapsing continuously.

e. During the vapor mass growth, no liquid is supplied to the liquid layer. The macrolayer is replenished with liquid only when the vapor mass departs or collapses.

f. The initiation of a new vapor mass after the departure or collapse of the previous one is almost instantaneous.

g. CHF is reached if the liquid layer completely evaporates during the vapor mass growth period.

Based on these postulates, CHF may be formulated as

$$\tau_g \; q_{CHF,SS,sub} = \rho_\ell h_{fg} \delta_{c,o,sub} \left(1 - \frac{A_v}{A_w}\right) (1 + K \; Ja) \quad , \tag{3}$$

where τ_g is the growth period of the bubble and $\delta_{c,o,sub}$ is the critical liquid-layer thickness at the steady-state subcooled boiling CHF. The critical liquid-layer thickness, $\delta_{c,o,sub}$, can be calculated by substituting $q_{CHF,SS,sub}$ for q in Eq. (2). This relation assumes that the effect of the surface heat flux on the Helmholtz instability wavelength may be formulated through a quasi-steady approach. We previously showed that the error associated with this assumption is within 1% in saturated pool boiling at atmospheric pressure.[1] At higher pressures and in subcooled pool boiling, the liquid-layer thickness is even thinner because the surface heat flux at CHF level is higher. Therefore, the error that occurs because of the quasi-steady formulation of the liquid-layer thickness is expected to be much smaller than 1%.

In Eq. (3), K is an empirical correction factor and primarily accounts for recirculation effects. However, it may also include the following effects.

i. After bubble collapse, part of the liquid supplied to the liquid layer comes from the thermal boundary layer. Therefore, it may be slightly heated over its bulk or far-field temperature.

ii. The liquid in contact with the heater is slightly superheated over its saturation temperature before it starts evaporating.

Note that the subcooled CHF model given by Eq. (3) is in the same form as the saturated CHF model of Haramura and Katto[7] given by

$$\tau_d q_{CHF,SS,sat} = \rho_f h_{fg} \delta_{c,o,sat} \left(1 - \frac{A_v}{A_w}\right) \quad , \tag{4}$$

where τ_d is the vapor mass hovering period in saturated pool boiling as given in App. A.

Using postulate (b), the ratio of the area covered by vapor to the total heater area, A_v/A_w, is assumed to be independent of the surface heat flux and subcooling. Therefore, the ratio remains the same as for saturated pool boiling. The error associated with this assumption is expected to be negligible because the quantity $[1 - (A_v/A_w)]$ is always close to unity, even for elevated pressures.[7]

In Eq. 3, the vapor mass growth period, τ_g, is difficult to estimate theoretically because the hydrodynamics of subcooled pool boiling is not as well understood as that of saturated pool boiling. In the current study, τ_g is quantified in terms of τ_d by using an empirical approach where the following functional form is assumed,

$$\tau_g = f_3(P, \Delta T_{sub}) \left(\frac{q_{CHF,SS,sub}}{q_{CHF,SS,sat}}\right)^{1/5} \tau_d \quad . \tag{5}$$

The dependence of the growth period on the one-fifth power of the surface heat flux is obtained from the solution of the equation of motion for an idealized bubble that was used by Katto and Haramura[7,8] to formulate the bubble hovering period in saturated pool boiling. By substituting Eq. (5) into Eq. (2) and rearranging the terms, the following relation may be obtained,

$$f_3(P, \Delta T_{sub}) = \left[\frac{\rho_f h_{fg} \delta_{c,o,sat}(1 - \frac{A_s}{A_w})}{\tau_d}\right]$$

$$\times \left(\frac{q_{CHF,SS,sat}}{q_{CHF,SS,sub}}\right)^{11/5} \left(\frac{1}{q_{CHF,SS,sub}}\right)(1 + K\ Ja) \quad . \tag{6}$$

The term within the brackets on the right-hand side (RHS) of Eq. (6) may be recognized as $q_{CHF,SS,sat}$ from Eq. (4). Thus, the vapor mass growth period in subcooled pool boiling may be obtained,

$$\tau_g = \tau_d \left(\frac{q_{CHF,SS,sat}}{q_{CHF,SS,sub}}\right)^3 (1 + K\ Ja) \quad . \tag{7}$$

By substituting Eq. (1) into Eq. (7), the following expression is obtained,

$$\frac{\tau_g}{\tau_d} = \frac{(1 + K^* Ja^*)}{(1 + 0.102 Ja^*)^3} \quad , \tag{8}$$

where the modified correction factor, K^*, is defined as

$$K^* = \frac{K}{\left(\frac{\rho_L}{\rho_g}\right)^{3/4}} \quad .$$

Figure 2 shows the ratio of the vapor mass growth periods as a function of the modified Jacob number, Ja^*, and the modified correction factor, K^*. As shown in this figure, as the subcooling increases (Ja^* increases), the vapor mass growth period becomes considerably smaller than the corresponding vapor mass hovering period in saturated pool boiling.

After the time constant of the subcooled pool boiling CHF is quantified using Eq. (8) and App. A, the transient CHF model in subcooled pool boiling may be obtained through a procedure similar to the one in saturated pool boiling.[1] The resulting transient CHF model is described in Sec. III.

III. TRANSIENT CHF CORRELATION

Equation (3) suggests that, after steady-state CHF is applied to the heater surface, dryout can be detected after a period of time, τ_g. During transient power conditions, the local heat flux increases during the growth period and complete evaporation of the liquid-layer thickness occurs sooner. By the time the surface is essentially dry, the local heat flux reaches a value higher than the steady-state CHF.

During the vapor mass growth period, it is assumed that no liquid is supplied to the liquid layer (postulate e). Thus, the rate of the liquid-layer thinning is governed by one of two

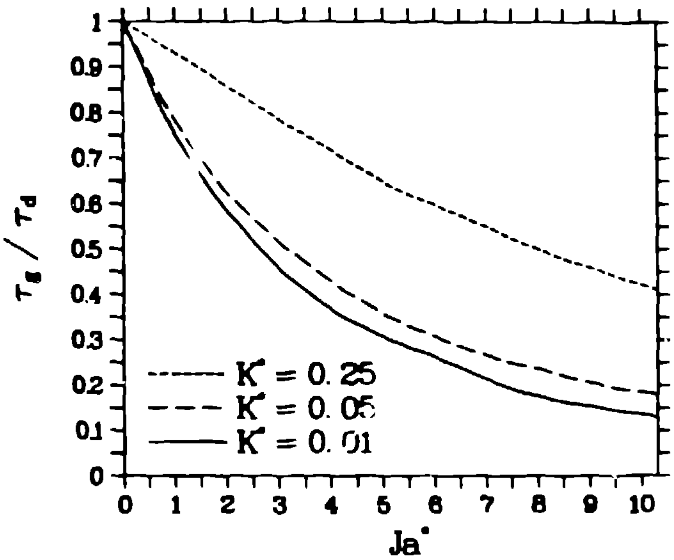

Fig. 2.
Relationship between the growth and hovering periods as a function of the modified Jacob number, Ja^*.

mechanisms: hydrodynamic instability or evaporation. This may be expressed mathematically as

$$\frac{d\delta}{dt} = \max\left[\left|\frac{\partial \delta_c}{\partial q}\frac{dq}{dt}\right| \ , \ \left|\frac{q}{f_2'(P, \Delta T_{sub})}\right| \right] \ , \tag{9}$$

where

$$f_2'(P, \Delta T_{sub}) = \rho_\ell h_{fg}\left(1 - \frac{A_v}{A_w}\right)(1 + K\ Ja) \ .$$

The first and second terms on the RHS of Eq. (9) correspond to hydrodynamic instability behavior and evaporation, respectively. Figure 3 illustrates the effects of the two mechanisms on the liquid-layer thinning. In this figure, the thinning process changes from being hydrodynamically to thermally controlled when

$$\left|\frac{\partial \delta_c}{\partial q}\ \frac{dq}{dt}\right| = \left|\frac{q}{f_2'}\right| \ , \tag{10}$$

which is called the switch-over point. The switch-over parameter, B_s, is defined in terms of the heat flux at the switch-over point, q_B, so that

$$B_s = \frac{q_B}{q_{\mathrm{CHF,SS,sub}}} \ .$$

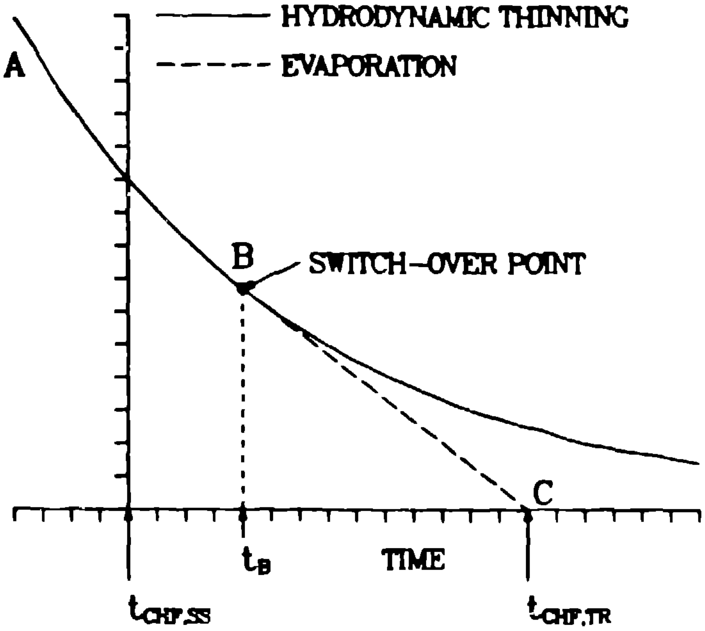

Fig. 3.
Schematic description of the switch-over between hydrodynamic and thermal thinning.

For an exponential increase in the surface heat flux given by

$$q(t) = q_i \exp\left(\frac{t}{\tau}\right) \quad , \tag{11}$$

the switch-over parameter, B_s, may be obtained for an exponential increase using Eq. 2 as

$$B_s = \left(\frac{2\tau_g}{\tau}\right)^{1/3} . \tag{12}$$

After the switch-over point between the two mechanisms is calculated, the transient CHF may be computed by evaluating one of the following integrals,

$$\delta_{c,o,\mathrm{sub}} = -\int_{t_{\mathrm{CHF,SS}}}^{t_B} \frac{\partial \delta_c}{\partial q} \frac{\mathrm{d}q}{\mathrm{d}t}\,\mathrm{d}t + \int_{t_B}^{t_{\mathrm{CHF,TR}}} \frac{q}{f_2'}\,\mathrm{d}t \quad , \quad if \;\; B_s \geq 1; \tag{13}$$

or

$$\delta_{c,o,\mathrm{sub}} = \int_{t_{\mathrm{CHF,SS}}}^{t_{\mathrm{CHF,TR}}} \frac{q}{f_2'}\,\mathrm{d}t \quad , \quad if \;\; B_s \leq 1 \; . \tag{14}$$

Equation (13) corresponds to the case shown in Fig. 3 where the switch-over occurs after $q_{CHF,SS}$, whereas Eq. (14) approximates the case where the switch-over occurs before $q_{CHF,SS}$. The second integral is an approximation because it is formulated as if a new vapor mass forms or the switch-over occurs when $q = q_{CHF,SS,sub}$. By using Eqs. (2) and (11), Eqs. (13) and (14) may be integrated to yield

$$\eta = \{1 - H(B_s - 1)\}\left(1 + \frac{\tau_g}{\tau}\right) + \{H(B_s - 1)\}1.89\left(\frac{\tau_g}{\tau}\right)^{1/3} \quad , \tag{15}$$

where $\eta = q_{CHF,TR,sub}/q_{CHF,SS,sub}$ and H represent the heavy-side step function. Note that Eq. (15) is the same as the transient CHF correlation developed for saturated pool boiling,[1] if $q_{CHF,SS,sub}$ and τ_g are replaced by $q_{CHF,SS,sat}$ and τ_d, respectively. Similar to the saturated pool boiling case, the first term of Eq. (15) represents an approximate value for the slower transients, whereas the second term corresponds to the minimum possible value of transient CHF for faster transients. This statistical aspect of the problem is analyzed further in Sec. V. Additional mathematical details of the above analysis may be found in the study of Pasamehmetoglu.[9]

IV. COMPARISON WITH DATA

In this section, Eq. (15) is compared with the data of Kuroda (as cited by Serizawa[4]). It must be realized that Eq. (15) is written in terms of the exponential period of the surface heat flux, whereas, in the experiments, the exponential period of the power generation rate is measured. Here, we will assume that a quasi-steady conduction mode may be used for heaters of small radius like the one used by Kuroda (as cited by Serizawa[4]). The quasi-steady conduction mode assumes that the surface heat flux and the power generation rates may be related through a simple volume-to-surface area ratio; thus, the exponential periods remain the same. Further discussion of the quasi-steady conduction mode may be found in Refs. 1 and 9.

In Fig. 4, the current theory (with $K = 1$) is compared with the data of Kuroda (as cited by Serizawa[4]) for 20 K subcooling. The prediction is favorable, although the data are slightly overpredicted for small values of τ. This overprediction may be attributed to the quasi-steady conduction approximation. The error involved by neglecting the hydrodynamic-thinning mechanism also is shown in Fig. 4. The dotted line shows that, if the evaporation is assumed to be the only thinning mechanism as suggested by Serizawa,[4] significantly large errors occur for small values of τ.

In Figs. 5 and 6, Eq. (15) is compared with the data for 40- and 60-K subcooling data, respectively. In both cases, using $K = 1$, the current theory underpredicts the data. The discrepancy increases as the subcooling increases. For $K = 1$, the growth periods calculated using Eq. (7) are 8.3 and 3.4 ms, respectively. These values are considerably lower than the 36.2-ms hovering period for saturated pool boiling at the same pressure. For $K = 10$, these values increase to 14.3 and 7.0 ms, respectively. The comparison of the current theory with $K = 10$ with the data also is shown in Figs. 5 and 6. The comparison is quite favorable. If more data were available, K could be correlated empirically as a function of ΔT_{sub}. As a general trend, K seems to increase with increased subcooling. A better interpretation of this comparison requires a better understanding of the steady-state hydrodynamics of subcooled

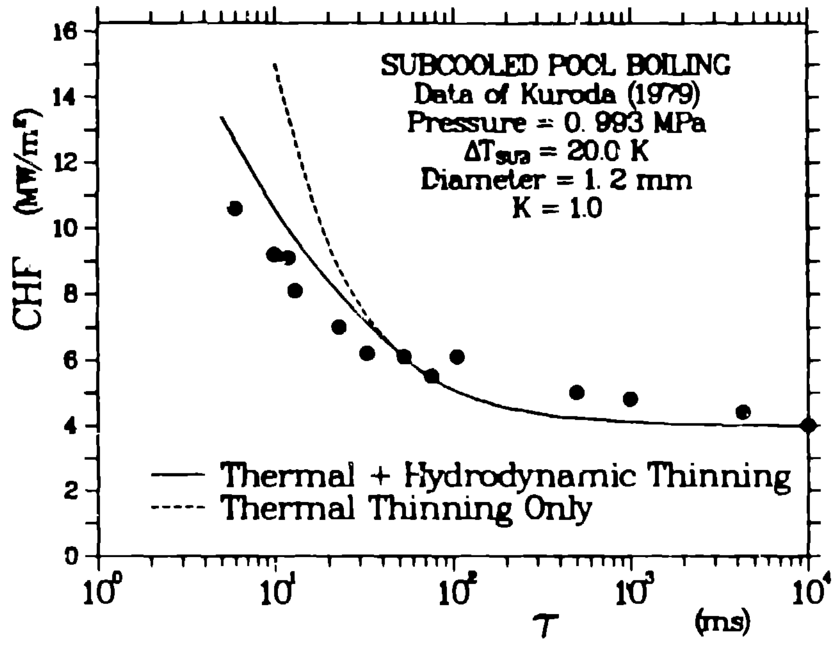

Fig. 4.
Comparison of the current theory with the 20-K subcooling data of Kuroda (as cited by Serizawa[4]).

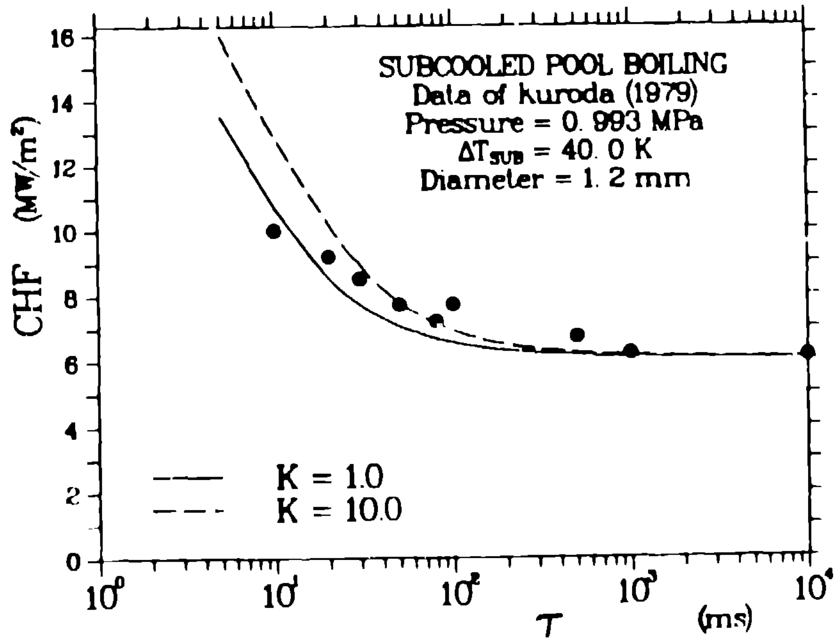

Fig. 5.
Comparison of the current theory with the 40-K subcooling data of Kuroda (as cited by Serizawa[4]).

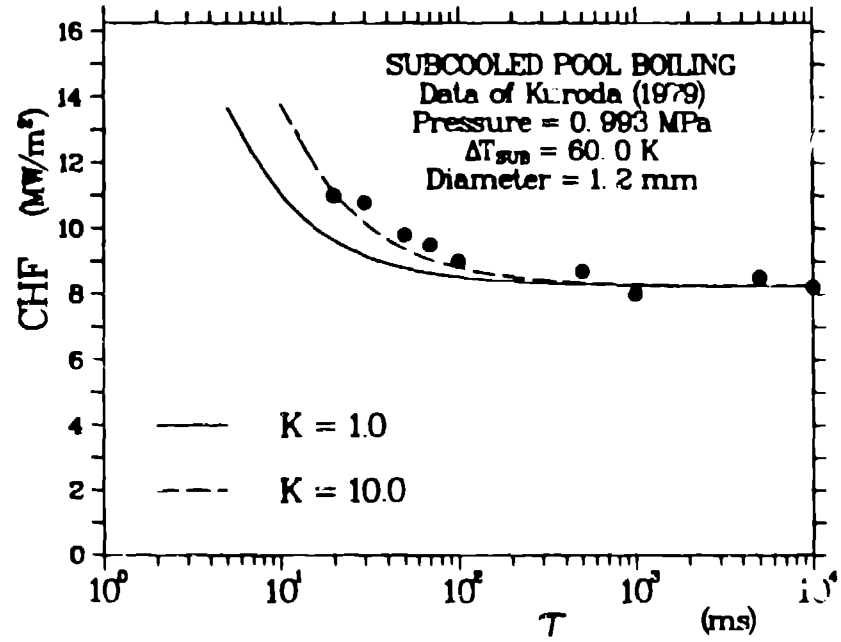

Fig. 6.
Comparison of the current theory with the 60-K subcooling data of Kuroda (as cited by Serizawa[4]).

pool boiling at high heat fluxes. The following items are important in evaluating the integrity of the steady-state model used in this study.

1. At high subcoolings, Eq. 1, after modification for small-diameter effects using the correlation of Haramura and Katto,[7] significantly underpredicts the steady-state CHF data of Kuroda (as cited by Serizawa[4]).
2. For high subcoolings, a well developed vapor mass regime as proposed in the current model may not exist, especially when the computed values of the growth period are on the order of a few milliseconds. With such small growth periods, the boiling configuration is closer to a discrete bubble pattern rather than a fully developed vapor mass pattern.
3. As a result of item 2, considerable liquid may be supplied to the liquid layer during the growth period.
4. Also as a result of item 2, when the growth period is very small, the waiting period may no longer be negligible.
5. For high subcoolings, the liquid-supply temperature and the recirculation effects may play an important role in computing the growth periods.

The current data comparison is not affected by the discrepancy in item 1, because the measured values of the steady-state CHF are used for comparison purposes. However, it shows the limitations of our knowledge in terms of subcooled pool boiling at high heat fluxes. The uncertainties outlined in items 2–5 are covered by the empirical constant K. For successful modeling over a wide range of subcooling, the current theory requires certain adjustments in K. However, because of the limited data, these adjustments could not be quantified in a correlation form. Development of a correlation requires additional data at various pressures and subcooling, as well as identifying the quantitative effect of the quasi-steady conduction approximation. In another study,[10] we showed that, even with certain simplifying assumptions, the effect of thermal storage within the heater may considerably affect the final prediction in saturated pool boiling, especially for small values of the exponential period, τ. The effect of thermal storage in subcooled pool boiling possibly is less pronounced. Nevertheless, it must be quantified before a strong statement can be made about the parameter K.

V. EFFECT OF THE RANDOM VAPOR MASS BEHAVIOR ON THE TRANSIENT CHF MODEL

So far, the magnitude of the transient CHF has been treated as a deterministic value. However, during transient boiling, the history of a given vapor mass may affect the final prediction; thus, a statistical value for the transient CHF is suggested. Such statistical effects are expected to be rather weak because of the strong influence of the hydrodynamic-thinning mechanism during fast transients. The hydrodynamic-thinning mechanism is effective regardless of the vapor mass behavior. During slower transients, the process becomes almost steady state. Therefore, the statistical effects also are expected to be small. Nevertheless, we quantified these effects for slow and fast transients and evaluated the results through data comparison.

First, the relatively slower transients are considered. During such transients, the switch-over from hydrodynamic to thermal thinning occurs before the surface heat flux reaches $q_{CHF,SS}$. Therefore, even before steady-state CHF, the macrolayer thinning is dominated by evaporation during the vapor mass hovering period. Previously, we characterized these transients based upon the magnitude of the switch-over parameter as $B_{\bullet} < 1$. The first term on the RHS of Eq. (15), which corresponds to slower transients, was obtained by assuming that the switch-over occurs or a new vapor mass is formed at $t = t_{CHF,SS}$. The calculated value does not correspond to either a minimum or maximum possible value of transient CHF but is used as an approximation between the maximum and minimum values. The corresponding macrolayer thickness follows the curve FG in Fig. 7.

To calculate the minimum possible value of transient CHF, we assume that a vapor mass is formed at point A in Fig. 7, where $t_D \leq t_A \leq t_{CHF,SS}$. For the macrolayer underneath this vapor mass to dry out in an evaporation mode at time t_G, the energy deposition must be large enough to evaporate all the liquid during the vapor mass hovering period. Thus, the following inequality must be satisfied,

$$(\delta_c)_{q = q_A} \leq \int_0^{\eta^{1/6}\tau_g} \frac{q_A \exp\left(\frac{t'}{\tau}\right)}{f_2'} \, dt' \quad , \tag{16}$$

where $t' = t - t_A$. The term $\eta^{1/6}\tau_g$ in Eq. (16) represents the vapor mass hovering period when the surface heat flux is equal to $q_{CHF,TR}$. This formulation assumes that the vapor mass growth period is almost independent of history effects and may be calculated as a function of the departure heat flux using a steady heat flux model. The validity of this assumption

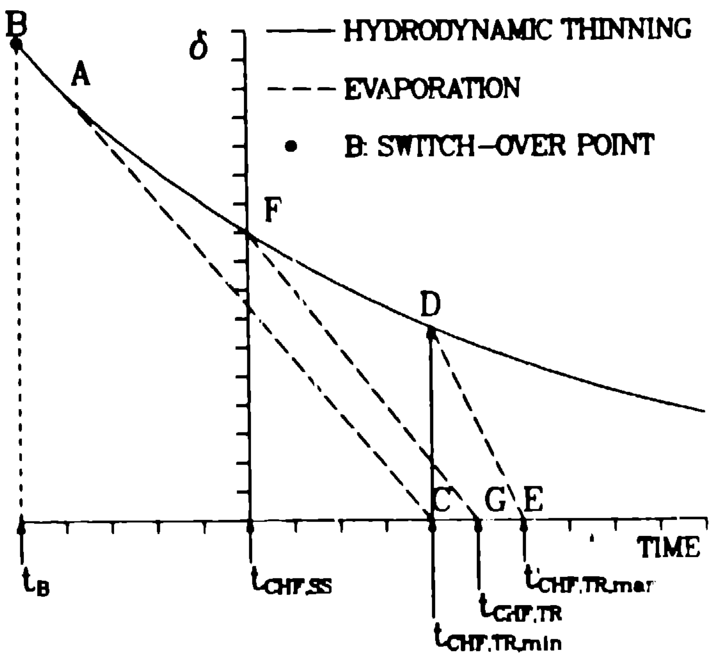

Fig. 7.
Macrolayer-thinning mechanism during slow transients.

for saturated pool boiling was shown in an earlier study.[11] By using Eqs. (2) and (3), the inequality in Eq. (16) gives

$$q_A \geq B_e q_{\mathrm{CHF,SS}} \left\{ \frac{1}{2\left[\exp\left(\eta^{1/5}\frac{B_e^3}{2}\right) - 1\right]} \right\}^{1/3} . \tag{17}$$

Because this analysis is concerned with slower transients where $B_e < 1$ and $\eta < 1.5$, we can safely approximate $\eta^{1/5}$ by 1. Thus, by rearranging the terms in Eq. (17), we obtain

$$\eta_{\min} = B_e \exp\left(\frac{B_e^3}{2}\right) \left\{ \frac{1}{2\left[\exp\left(\frac{B_e^3}{2}\right) - 1\right]} \right\}^{1/3} . \tag{18}$$

This result is valid only for slow transients where dryout under a given vapor mass occurs because of evaporation only during its hovering period. Therefore, q_A must be greater than or equal to the switch-over heat flux, q_B, which is defined as $B_\bullet q_{CHF,SS}$. Thus, Eq. (17) yields

$$\left\{ \frac{1}{2\left[\exp\left(\frac{B_\bullet^3}{2}\right) - 1\right]} \right\}^{1/3} \geq 1 \quad , \tag{19}$$

which gives

$$B_\bullet \leq 0.93 \quad .$$

The vapor mass that can lead to the earliest dryout must be formed when $q = 0.93\ q_{CHF,SS}$. Any vapor mass formed earlier will depart before dryout, whereas the vapor masses formed after will lead to dryout before their departure.

The maximum possible value of transient CHF for the same slow transient corresponds to the case where the vapor mass departs (or collapses) an instant before dryout (point C in Fig. 7) and fresh liquid replenishes the macrolayer. Thus, the macrolayer thickness follows the path ACDE. The replenished macrolayer thickness at point D is controlled by the hydrodynamic mechanism that determines the thickness based on the transient heat flux at that instant in time. The corresponding maximum transient CHF may be obtained through the solution of the following integral,

$$(\delta_c)_{q=q_{CHF,TR,min}} = \int_0^{t'_{CHF,TR,max}} \frac{q_{CHF,TR,min} \exp\left(\frac{t'}{\tau_\bullet}\right)}{f'_2}\, dt' \quad , \tag{20}$$

where $t' = t - t_{CHF,TR,min}$. By rearranging the terms, Eq. (20) yields

$$\eta_{max} = \eta_{min} + \frac{B_\bullet^3}{2\eta_{min}^2} \quad , \tag{21}$$

where η_{min} is given by Eq. (18).

During faster transients ($B_\bullet \geq 0.93$), the macrolayer thinning under the vapor mass leading to the earliest possible dryout is caused partly by hydrodynamic thinning. For these transients, the macrolayer-thickness history in the vicinity of the transient CHF is shown in Fig. 8. A vapor mass initiated after the switch-over point leads to dryout because the surface heat flux is high enough to evaporate the macrolayer before its departure (or collapse); however, a vapor mass initiated before the switch-over point may depart before dryout (point C), depending upon its growth period. As shown in Fig. 8, the behavior of the vapor mass before the switch-over point ($t = t_B$) does not affect the liquid-layer thickness. The only time the macrolayer thickness is affected by the vapor mass departure is when this departure occurs after the switch-over time. Therefore, what we previously postulated to be $t_{CHF,TR}$ actually

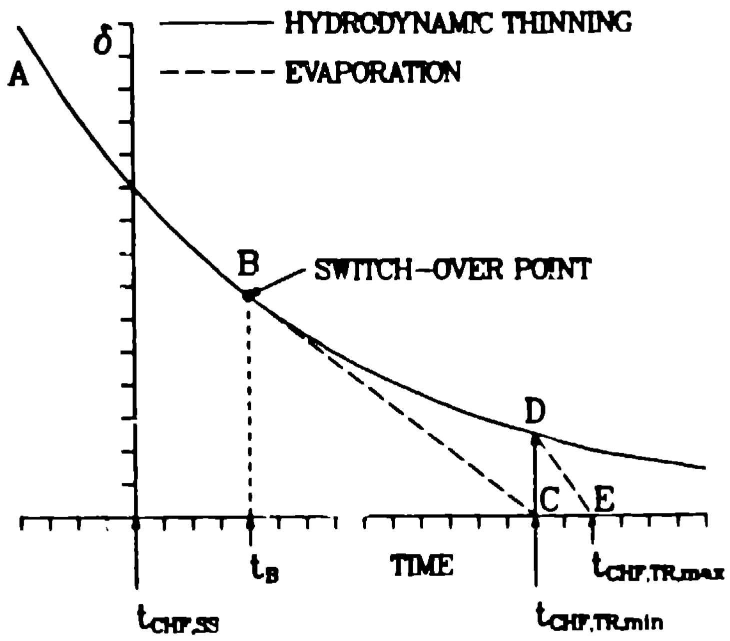

Fig. 8.
Macrolayer-thinning mechanism during fast transients.

applies if the vapor masses do not depart between t_B and $t_{CHF,TR}$. Thus, the transient CHF, η, calculated through this approach must be the minimum possible magnitude, η_{min}, which is given by the second term on the RHS of Eq. (15). Thus, for fast transients,

$$\eta_{min} = 1.5\ B_s \quad . \tag{22}$$

The maximum possible value corresponds to the case where the vapor mass departs just before dryout ($t = t_{CHF,TR,min}$). Thus, the liquid-layer thickness follows the path ABCDE in Fig. 8. Through an analysis similar to that for slow transients, it can be shown that the maximum heat flux is given by Eq. (21), where η_{min} must be replaced by Eq. (22).

We must remember also that the above analysis is not applicable to very fast transients. If the transient is fast enough that the very first vapor mass that forms remains on the surface until transient CHF occurs, the transient CHF becomes a deterministic rather than a probabilistic value. Actually, in these cases, it is more appropriate to talk about a vapor blanket overlaying the macrolayer rather than vapor masses because, without departure, the Taylor wave pattern for individual vapor masses may not be distinguished. However, in subcooled pool boiling, the growth periods are small and the time-to-CHF is longer. Thus, we tentatively assume that, for $\tau \geq 10$ ms, the boiling has sufficient time to establish a vapor mass boiling regime. This assumption is based upon the Moissis-Berenson transition criterion,[12] which is valid only for saturated pool boiling. This criterion is used as a first-order approximation for pool boiling with low subcooling.

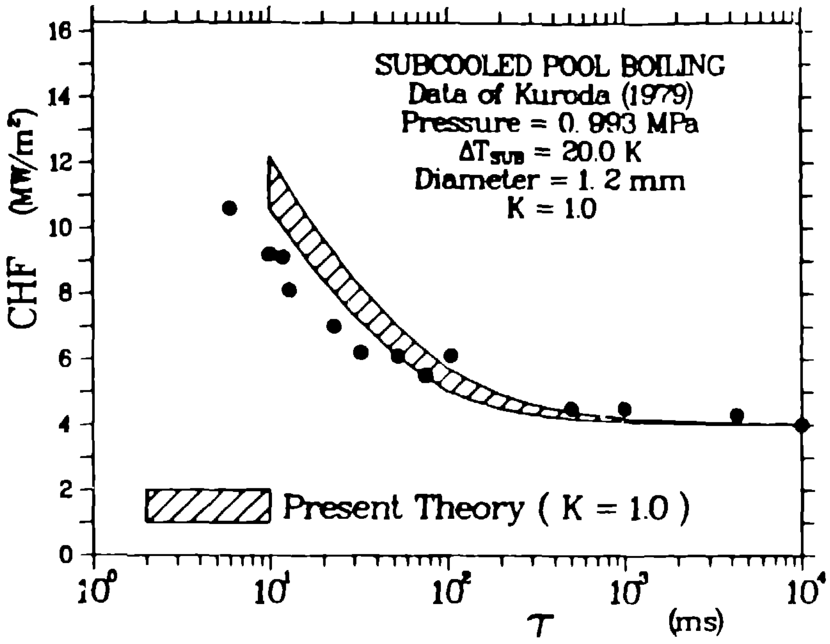

Fig. 9.
Comparison of the current theory with the 20-K subcooling data of Kuroda (as cited by Serizawa[4]) including the random vapor mass behavior.

We can summarize this statistical analysis by the following expressions,

$$\eta_{min} = \{1 - H(B_* - 0.93)\}B_* \exp\left(\frac{B_*^3}{2}\right)\left\{\frac{1}{2\left[\exp\left(\frac{B_*^3}{2}\right) - 1\right]}\right\}^{1/3}$$

$$+\{H(B_* - 0.93)\}1.5B_* \tag{23}$$

and

$$\eta_{max} = \eta_{min} + \frac{B_*^3}{2\eta_{min}^2} \; . \tag{24}$$

Figure 9 shows the range covered by Eqs. (23) and (24) compared with the low subcooling (20-K) data of Kuroda (as cited by Serizawa[4]). As shown in this figure, the current theory suggests a small data scatter and is in agreement with such scatter during slower transients. It also is worth noting that, if evaporation is assumed to be the only thinning mechanism, as suggested by Serizawa,[4] the scatter for fast transients will be much larger. This is contradicted by the experimental data.

VI. SUMMARY AND CONCLUSIONS

In this paper, a theoretical prediction of the CHF during power transients in subcooled pool boiling is presented. Similar to our earlier study,[1] the transient CHF is a function of the vapor mass growth period. The growth period may be quantified for saturated conditions by solving the idealized bubble growth equation, as summarized in App. A. For subcooled conditions, the corresponding growth period is shorter.[6] However, the hydrodynamics of subcooled pool boiling at high heat fluxes is not as well understood as that of saturated pool boiling. Consequently, it is difficult to quantify the vapor mass growth period in subcooled pool boiling.

In this paper, a simple steady-state CHF model is developed to find a quantitative relationship between the vapor mass growth periods at saturated and subcooled conditions. The resulting relation, which is a function of the pressure and the degree of subcooling, is used along with the theory developed in our previous study for saturated conditions[1] to develop a transient CHF correlation given by Eq. (15). Using the quasi-steady conduction approximation, the theory is compared with the experimental data of Kuroda (as cited by Serizawa[4]). The comparison with these data from horizontal cylindrical heaters with small diameters is favorable, as shown in Figs. 3–5.

The effect of random vapor mass behavior also is analyzed. The corresponding minimum and maximum possible values of the transient CHF, which form a rather narrow envelope, suggest a minimum data scatter, as shown in Fig. 8. Nevertheless, such small scatter is consistent with the scatter experimentally observed during slow transients.

An improvement in the predictive capabilities of the current theory is possible if (1) a better coupling between the heat generation rate and surface heat flux is established and (2) the hydrodynamics of subcooled pool boiling at high heat fluxes near CHF is better understood.

Our current study clearly shows that not only the transient but also the steady-state aspects of subcooled pool boiling at high heat fluxes near CHF are not nearly as well understood as those of saturated pool boiling. Both thermal and hydrodynamic aspects of this problem require further analysis before a stronger statement can be made about the current model. Despite these difficulties, the current model predicts the data with moderate subcoolings exceptionally well.

APPENDIX A

VAPOR MASS HOVERING PERIOD IN SATURATED POOL BOILING

In this appendix, the equation given by Katto and Haramura[7,8] that estimates the hovering period is summarized. This equation is obtained by solving the equation of motion for an idealized bubble. The hovering period[7,8] is given by

$$\tau_d = \left(\frac{3}{4\pi}\right)^{1/5} \left[\frac{4(\xi\rho_f + \rho_g)}{g(\rho_f - \rho_g)}\right]^{3/5} V_1^{1/5} \quad , \qquad (A-1)$$

where $\xi = 11/16$ and, for cylindrical heaters with small radii, V_1 is given by

$$V_1 = \frac{\pi d \lambda'_D q}{\rho_g h_{fg}} \quad . \qquad (A-2)$$

In Eq. (A-2), λ'_D is the modified unstable Taylor wavelength. It is modified to account for the additional effect of surface tension along the curvature and is given by

$$\lambda'_D = \frac{2\pi\sqrt{3\left[\frac{\sigma}{g(\rho_f-\rho_g)}\right]}}{\sqrt{\left[1+\frac{2\sigma}{d^2 g(\rho_f-\rho_g)}\right]}} \quad . \qquad (A-3)$$

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